

Joint Observations of Marine Lightning Over the Atlantic by the FORTE Satellite and the United Kingdom Meteorological Office Sferics Array

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Abstract

During 1998 and 1999, the FORTE satellite conducted occasional observations of radio-frequency emissions from lightning over the Atlantic Ocean. At the same time, the Atlantic was reasonably well covered by a sferics-receiver array operated by the United Kingdom Meteorological Office. Comparison of the two systems' signals indicates that subsets of each dataset represent correlated observations of the same strokes. The storms successfully seen in common by the two systems are primarily over the ocean, with relatively few strokes over land. Because "groundtruthing" of lightning over the oceans is in only a primitive stage, we will present the characteristics of the strokes and flashes observed in common by these two systems, and in particular the differences from our prior experience with RF/sferic correlations between FORTE and NLDN.

Acknowledgements

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Introduction

The United Kingdom Meteorological Office operates a long-range lightning-detection system called ATD (Daly *et al*, “Results from the upgraded ATD sferics lightning detection system of the Met Office (UK)”, in Proceedings of 2000 International Lightning Detection Conference, Tucson AZ November 7-8, 2000.) Using a narrow-band system near 10kHz, with stations in the UK, Cyprus, and Gibraltar, the ATD system can perform some detections of lightning strokes over long distances, including to the Caribbean and United States east-coastal areas. The efficiency of these detections at long range has not been precisely characterized. These detections rely on ionospheric ducting of the VLF signal, so it is not readily possible to retrieve information on either the stroke type or the effective vertical current in the stroke.

One of the odd features of ATD long-range detection behavior near the eastern United States is a strong affinity for detection of strokes over the ocean, as opposed to land. We will address this in Section A.

The FORTE satellite (see http://nis-www.lanl.gov/nis-projects/forte_science/ for extensive references and downloadable PDF files) carries a suite of optical and radiofrequency (RF) instruments for global monitoring of lightning. Previously we had studied the relationship of FORTE RF lightning signatures to National Lightning Detection Network (NLDN) stroke detections and characterizations (Jacobson, A.R., K.L. Cummins *et al* FORTE radio-frequency observations of lightning strokes detected by the National Lightning Detection Network, *J. Geophys. Res.*, 105 (D12), 15,653, 2000.) The work described below extends this approach, to the limited extent possible, to studying the relationship of FORTE VHF signatures to the longer-range, and in particular, the maritime strokes detected by the ATD system.

Section A: Groundtruthing ATD with NLDN

The ATD achieves some detection of strokes near the United States east coast. The most important tool in groundtruthing ATD in this region has been comparison with contemporaneous data from U. S. National Lightning Detection Network (NLDN), in a collaboration between the FORTE team and Global Atmospheric, Inc, the array's developer/owner/operator. The NLDN is a system of low-frequency (LF; 30-300 kHz) and very-low-frequency (VLF; 3-30 kHz) electromagnetic sensors in an array covering lightning throughout the continental United States [Cummins, K.L., M.J. Murphy, E.A. Bardo, W.L. Hiscox, R. Pyle, and A.E. Pifer, Combined TOA/MDF technology upgrade of U. S. National Lightning Detection Network, *J. Geophys. Res.*, *103* (D8), 9035-9044, 1998]. The NLDN is comprised of 59 LPATS-III Time-of-Arrival (TOA) sensors and 47 IMPACT sensors that provide both TOA and direction-finding information. The median location accuracy provided by the NLDN is 500 meters, and the estimated flash detection efficiency varies between 80 and 90 percent, for peak currents greater than 5 kA.

The NLDN sensors are responsive to radiation field signals in the LF and VLF frequency ranges, and are thereby sensitive to ground-wave lightning return-stroke fields over a spatial range of about 30 to 650 km. They are also responsive to lightning-produced VLF fields that have been reflected by the ionosphere, and to a subset of fields produced by cloud discharges that emit significant energy in the LF frequency range. The IMPACT sensors are designed to reject many of these cloud discharges and "reflected" signals, based on waveform criteria, but the LPATS-III sensors accept a broader range of waveshapes.

The standard NLDN lighting data are carefully quality controlled and limited to minimize mislocated “outlier” events, employing specific criteria. For the purposes of this study, we reprocessed the raw sensor from the LPATS-III sensors employing relaxed criteria, in order to maximize the detection of both cloud discharges and distant CG discharges. Specifically, “unverified” locations produced by three LPATS-III (TOA) sensors were accepted, no maximum limit was set for the distance between a sensor and the discharge location, and a number of waveform-consistency criteria were relaxed to accommodate ionospherically propagated signals. The resulting dataset therefore included some very distant CG lighting discharges (sferics), occurring several thousand km outside the network, as well as very energetic cloud discharges occurring within or near the network. Given the relaxed criteria, the dataset also included numerous outliers. However, for groundtruthing of ATD, only those strokes within 625 km of the nearest participating NLDN sensor were used.

The located lightning discharges were classified as follows. Events for which all contributing sensors reported a narrow pulse-width, identified by a peak-to-zero time of less than 10 μ s, were identified as cloud discharges. All other discharges were identified as cloud-to-ground. For those events in which the closest reporting sensor was more than 650 km from the calculated location, the estimated signal strength (peak current) was set to zero. This assignment reflects the uncertainty in the source strength when the ground wave becomes smaller than the ionospheric reflection.

Figure A1 shows the selection box for using NLDN to groundtruth ATD near the east coast of the United States.

Figure A2 shows the time relationship of approximately co-located NLDN stroke detections and ATD strokes detections. The central peak is at an offset range (+2 to -10 milliseconds) because of a systematic timing offset in ATD declared stroke times. This central peak corresponds to prompt, reliable coincidences between NLDN and ATD.

Figure A3 shows the time (UT) distribution of NLDN strokes in the selection box. The dashed curve is for the parent population of all NLDN strokes during epochs when the ATD system was operating and taking data. The solid curve is for the subset of that population for which there are tightly coincident (+2 to -10 milliseconds). Note dramatically different times of occurrence of the peaks in the parent population versus the ATD-coincident population. This may be due to the more favorable LF propagation during the hours ~01 to 08 UT, when much of the Atlantic region is in relative darkness. The effect of relative darkness is to suppress ionospheric D-layer attenuation, and hence to lessen the LF amplitude attenuation on the propagation path to the ATD sensors, all of which are east of the Atlantic.

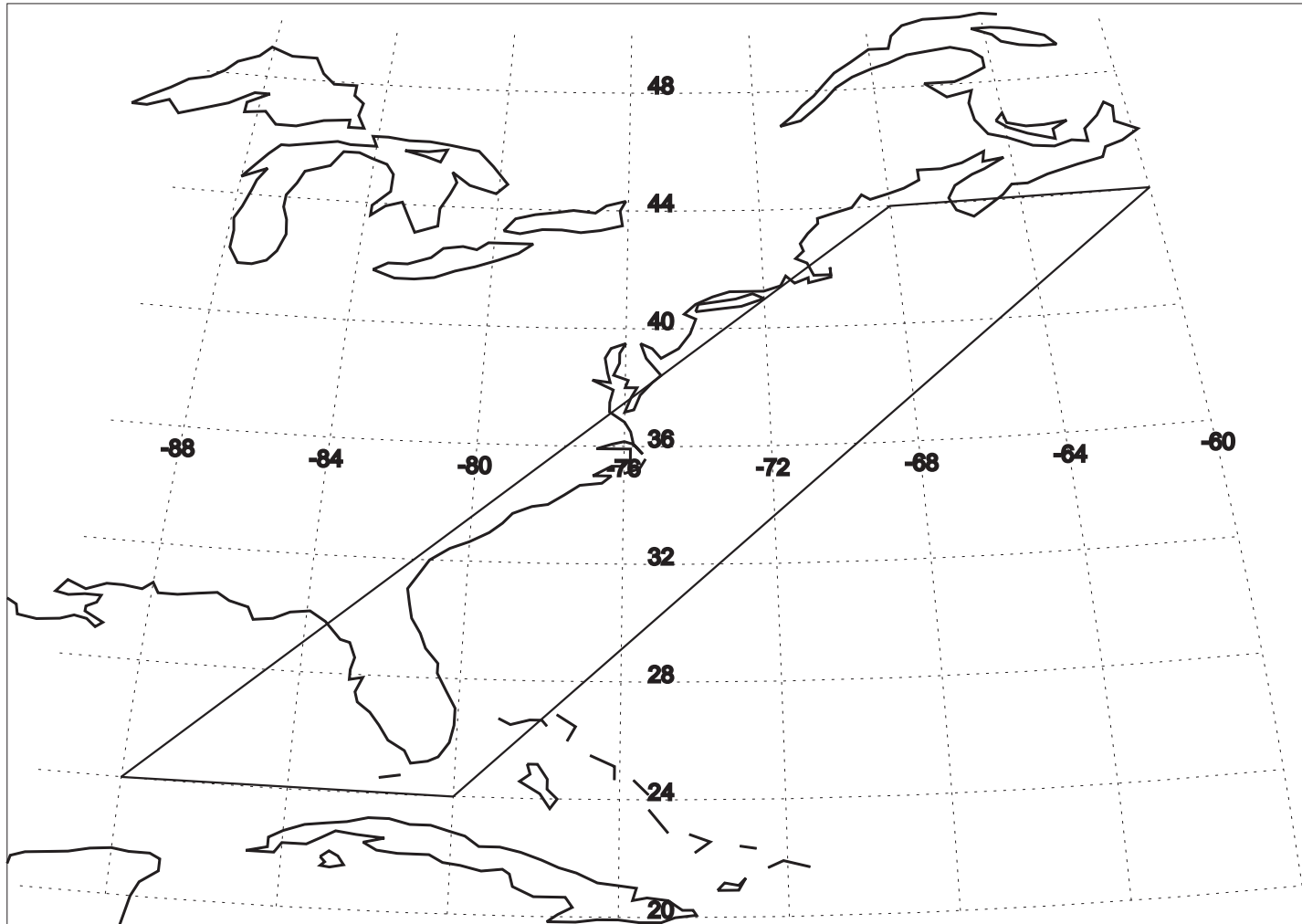


Figure A1: Selection box for East-coastal comparison of UK Met Office's ATD strokes with NLDN ground truth. The box is chosen so that although it is mainly offshore (where the majority of ATD events lie), the region is close enough to the coast that most NLDN events in the box are also within 650 km from the nearest participating NLDN sensor. This ensures that the NLDN can characterize the stroke type and estimate the effective vertical current.

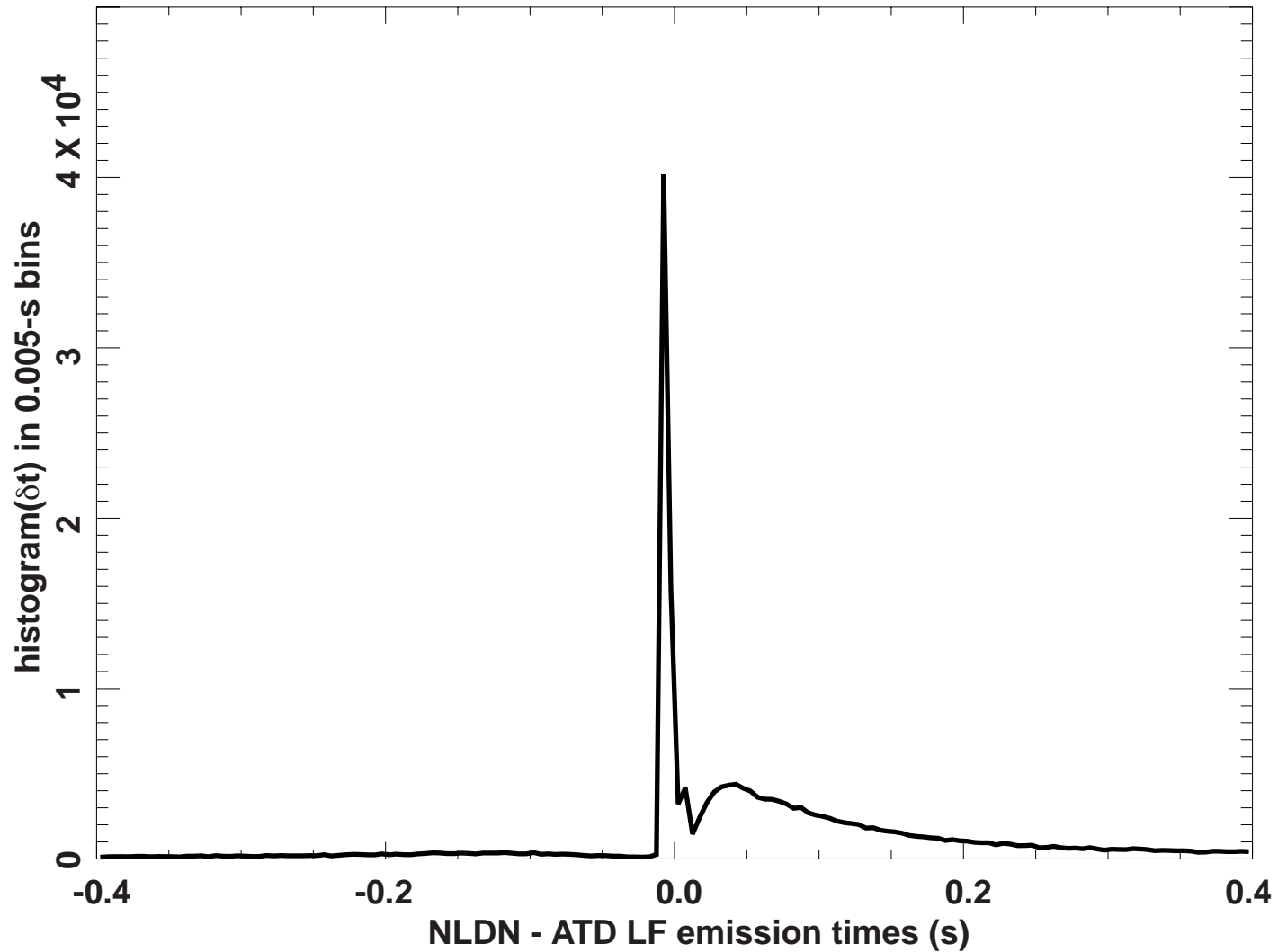


Figure A2: Histogram of NLDN-ATD emission times, for NLDN events within the selection box shown in Figure A1. The central peak is for both systems' detection of the same stroke. The asymmetric shoulder on the right is due to the ability of NLDN to detect subsequent strokes (in flashes with multiplicity > 1), during the “dead time” when ATD is unable to trigger.

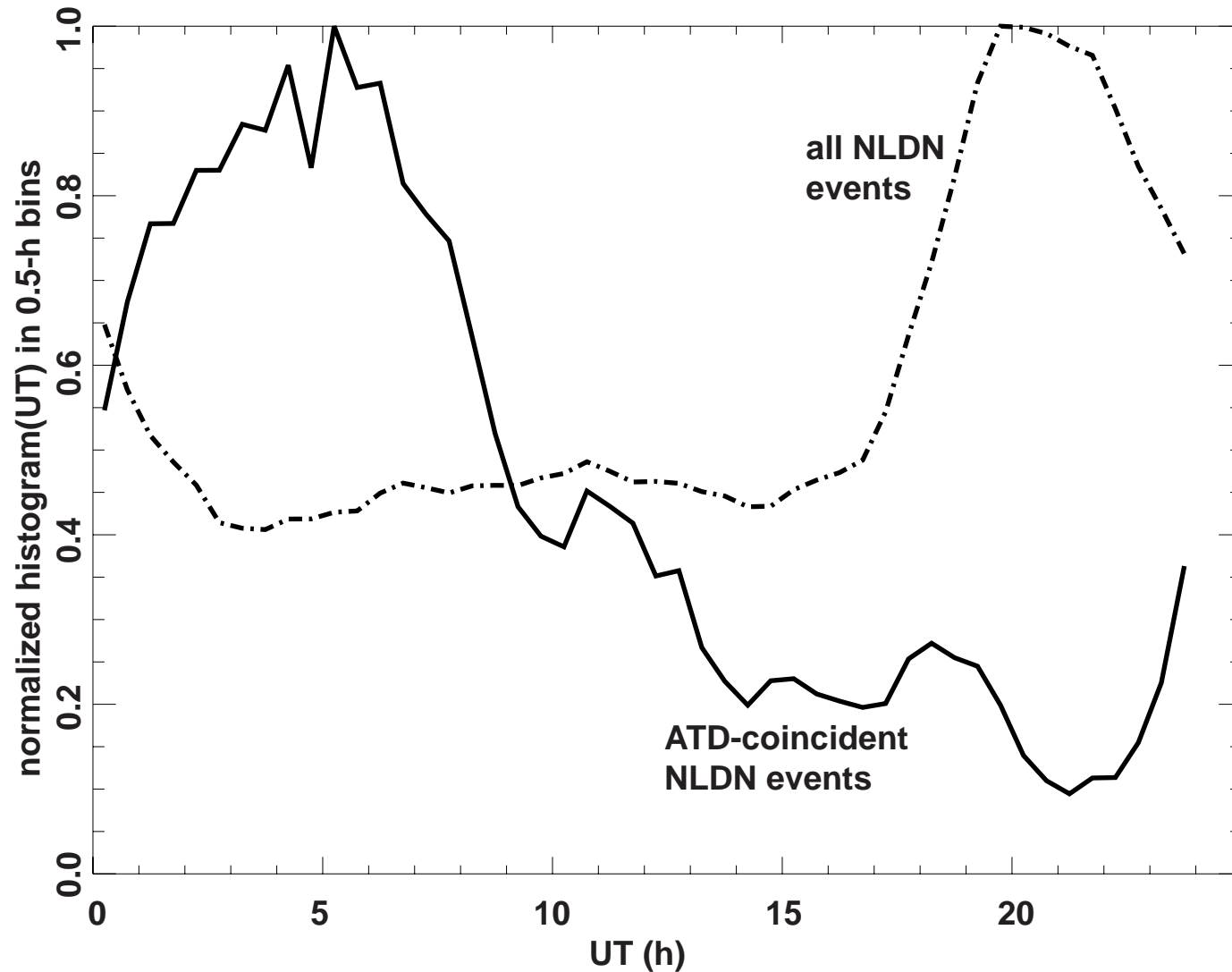


Figure A3: Dashed curve: Histogram of all NLDN events in the selection box (see Figure A1), versus Universal Time. The peak at ~20 UT corresponds to the peak local times (~15-16 H local) for lightning in the selection box. Solid curve: Similar to dashed curve, but exclusively for those NLDN events that are also detected by the ATD system. The peak at ~5 UT differs radically from the NLDN's own peak (see dashed curve), and we speculate that this is due to more favorable propagation during the hours ~01 to 08 UT, when much of the Atlantic region is in darkness. The effect of darkness is to suppress ionospheric D-layer attenuation, and hence to lessen the amplitude attenuation on the propagation path to the ATD sensors, all of which are east of the Atlantic.

The next question is, *why are the ATD long-range-detected strokes so likely to occur over the ocean, as opposed to occurring over land?* It has been suggested (Martin Murphy, private communication 2001) that this could be due to a combination of two things: First, there is a well-known tendency for oceanic return strokes to be, on average, somewhat higher-current than terrestrial return strokes. Second, at sufficiently long range any detection system, and certainly ATD is no exception, is likely to detect only the high-amplitude tail of the event distribution. Putting these two considerations together, it is plausible that we might expect ATD's long-range-detected stroke density to fall-off appreciably as one goes from ocean to land.

We test this as follows:

Figure A4 shows the dependence of NLDN stroke incidence in the selection box, as a function of NLDN-determined effective peak vertical current. The dashed curve is for the parent population of all NLDN strokes during epochs when the ATD system was operating and taking data. The solid curve is for the subset of that population for which there are tightly coincident (-2 to +10 milliseconds). *Each curve is separately and arbitrarily normalized to have peak value of unity, in order for easy visualization of the curve's shape.* Figure A5 shows the fraction of NLDN events in the selection box that have tightly-coincident colocated ATD events, as a function of peak current. This is, in effect, an approximate efficiency of ATD long-range detection. The solid curve is for the peak of daylight for the Atlantic sector, while the dashed curve is for the peak of darkness. The systematic enhancement of detection efficiency for dark conditions has already been noted (see Figure A3). What is new in Figure A5 is the evidence that the ATD detection efficiency has a steep, positive correlation with the effective peak vertical current amplitude. This tends to support the idea (put forward by Martin Murphy, private communication 2001) that the ocean/land difference in detection may be just a proxy for a steep underlying current dependence.

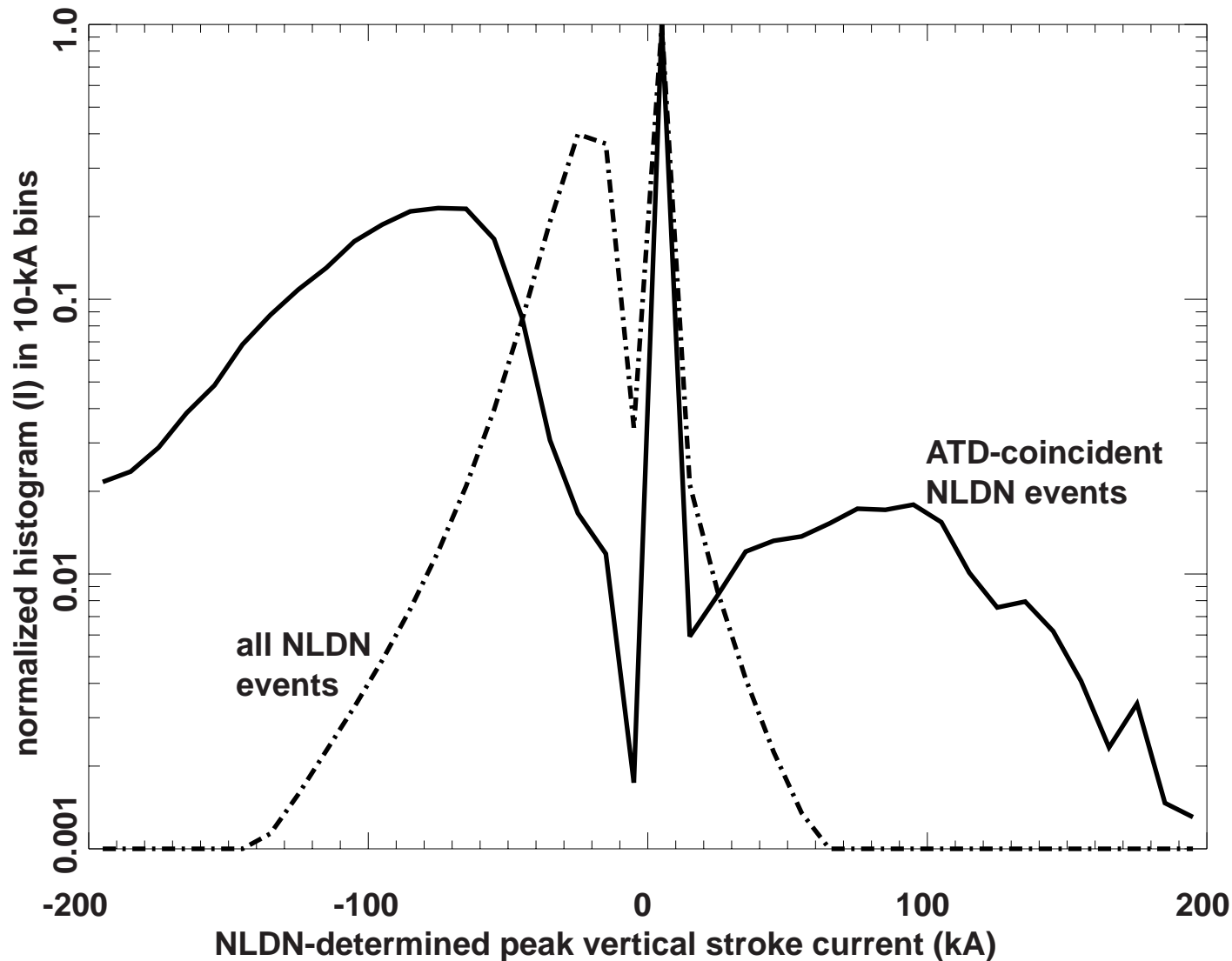


Figure A4: Relative histograms of all NLDN strokes in the selection box (see Figure A1) (dashed curve) and of NLDN strokes also detected by the ATD system in the selection box (see Figure A1) (solid curve), as a function of NLDN-estimated peak effective vertical current. *Each histogram has been separately normalized to unity* for easy display. (See next figure, Figure A5, which gives an ATD detection efficiency using NLDN as a ground-truth.)

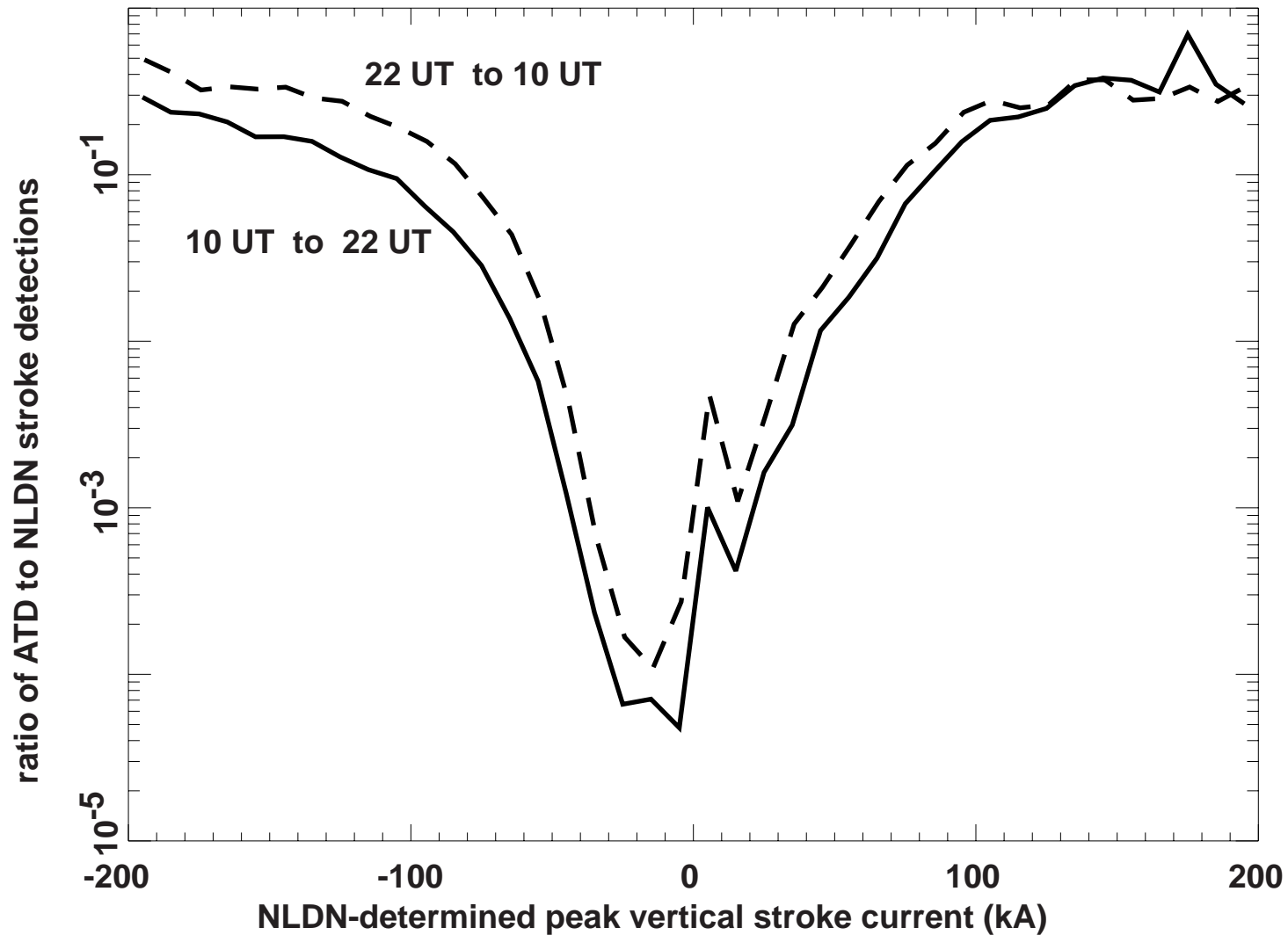


Figure A5: Fraction of NLDN strokes in the selection box (see Figure A1) that are also detected by the ATD system, as a function of the NLDN-estimated peak effective vertical current. There is a two-order-of-magnitude improvement in ATD detection efficiency, from the lowest-current strokes to the highest-current strokes. The solid curve is for the peak of Atlantic being sunlit; the dashed curve is for the peak of Atlantic being in darkness (see Figure A3).

Section B: Correlations of ATD strokes with FORTE RF events

The prior experience in correlating FORTE RF events with ground-based stroke-detection arrays had been with NLDN (Jacobson, A.R., K.L. Cummins *et al*, FORTE radio-frequency observations of lightning strokes detected by the National Lightning Detection Network, *J. Geophys. Res.*, 105 (D12), 15,653, 2000.) That study showed a time-difference distribution like that in Figure B1, in which the horizontal axis is the NLDN stroke time minus the propagation-corrected FORTE estimate of RF emission time. The upper panel of Figure B1 uses a 1-millisecond bin width, so the peak-to-background ratio is artificially suppressed. This is corrected in the lower panel, which uses a 0.1-millisecond bin width. The purpose of the upper panel, with its domain of ± 200 milliseconds, is to show that the central peak is relatively isolated, without a shoulder that would be evidence of the flashes' containing multiple strokes. Indeed, when we explicitly count the same-flash neighbor strokes of NLDN strokes that have FORTE RF coincidences, we find that the typical such flash has multiplicity=1. (This is true even when we down-select to only -CG flashes, whose parent NLDN distribution has multiplicity >2 .)

Figure B2 shows the distribution of ATD-/propagation-corrected FORTE RF emission times, with a 2-millisecond bin width. This differs qualitatively from the NLDN/FORTE picture of Figure B1, in that the ATD/FORTE distribution shows a prominent asymmetric hump on the left of the central peak. This is analogous to the asymmetric hump on the *right* of Figure A2, *viz*, the inability of the ATD system to “reload” fast enough to detect subsequent strokes after detecting the first stroke.

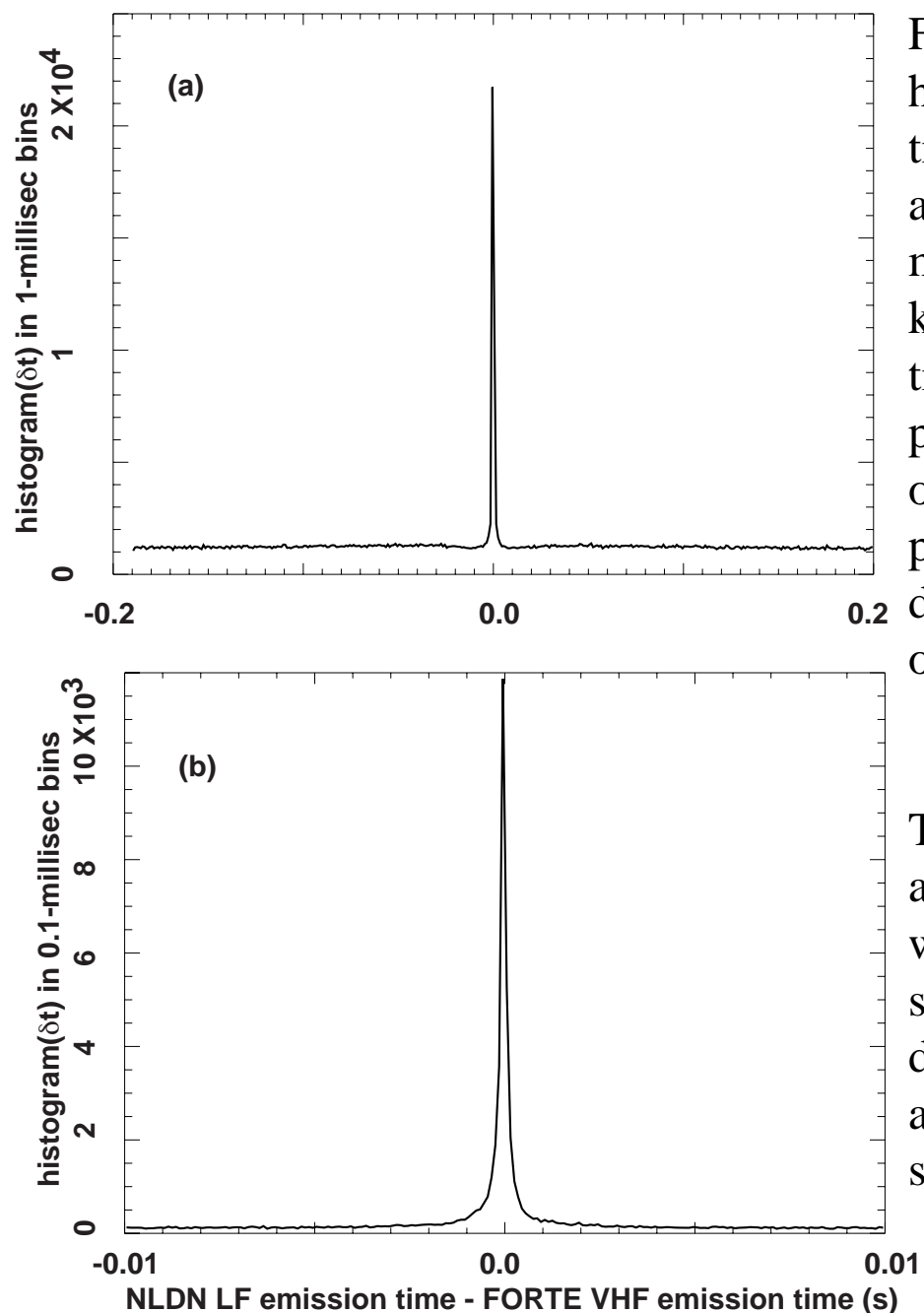


Figure B1: For reference, these are histograms of the NLDN/FORTE-VHF time difference, using (a) a 1-millisecond bin and a ± 0.2 -sec domain, and (b) a 0.1-millisecond bin and a ± 0.01 -sec domain. The key point is that for FORTE-VHF events' time relationship to NLDN, the coincident points mainly occur for NLDN strokes that occur in flashes of multiplicity=0. A second point is that the intrinsic width of the distribution (see lower curve) is on the order of ~ 0.2 millisecond.

The data in this figure are from the 1998 and 1999 FORTE/NLDN joint study, during which two summer seasons were intensively studied for FORTE VHF/NLDN coincident detections, with NLDN detecting the sferic and FORTE detecting very-high-frequency signals closely coincident with the stroke.

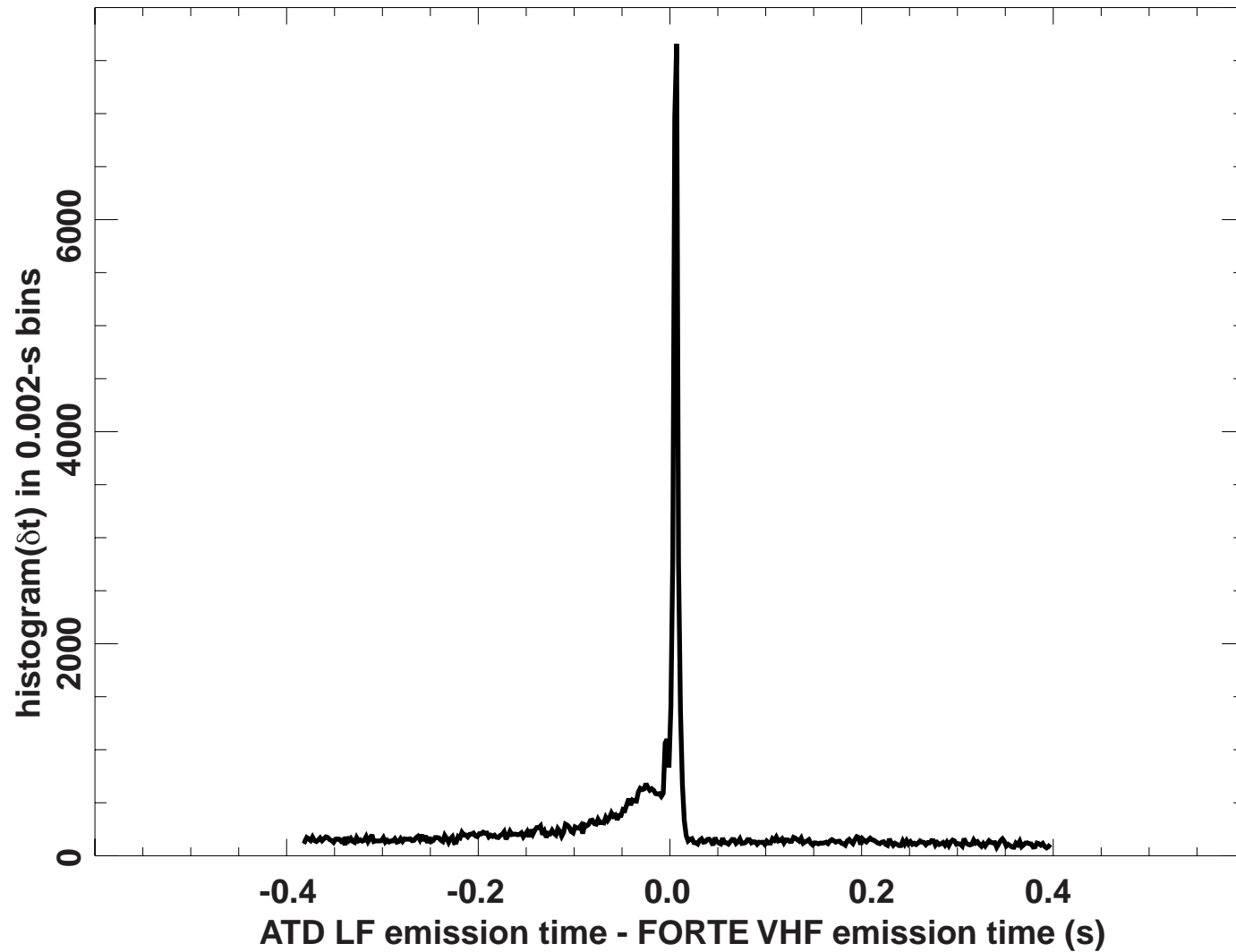


Figure B2: Histogram of the ATD/FORTE-VHF time differences, with a 2-millisecond bin. The asymmetric shoulder on the left is due to the failure of ATD to detect subsequent pulses, due to the system recovery time between event registrations. (There is also an overall ~5-millisecond systematic shift in the ATD times, relative to ground truth.)

The map of all ATD strokes detected during FORTE visibility is shown in Figure B3. This is an all-season average over 1998 and 1999, weighted by occurrence of FORTE passes.

The subset of the events in Figure B3 for which there are tightly coincident FORTE RF events are shown in Figure B4. These FORTE-coincident strokes in Figure B4 are distributed geographically in a manner that is approximately the same as the overall ATD distribution shown in Figure B3.

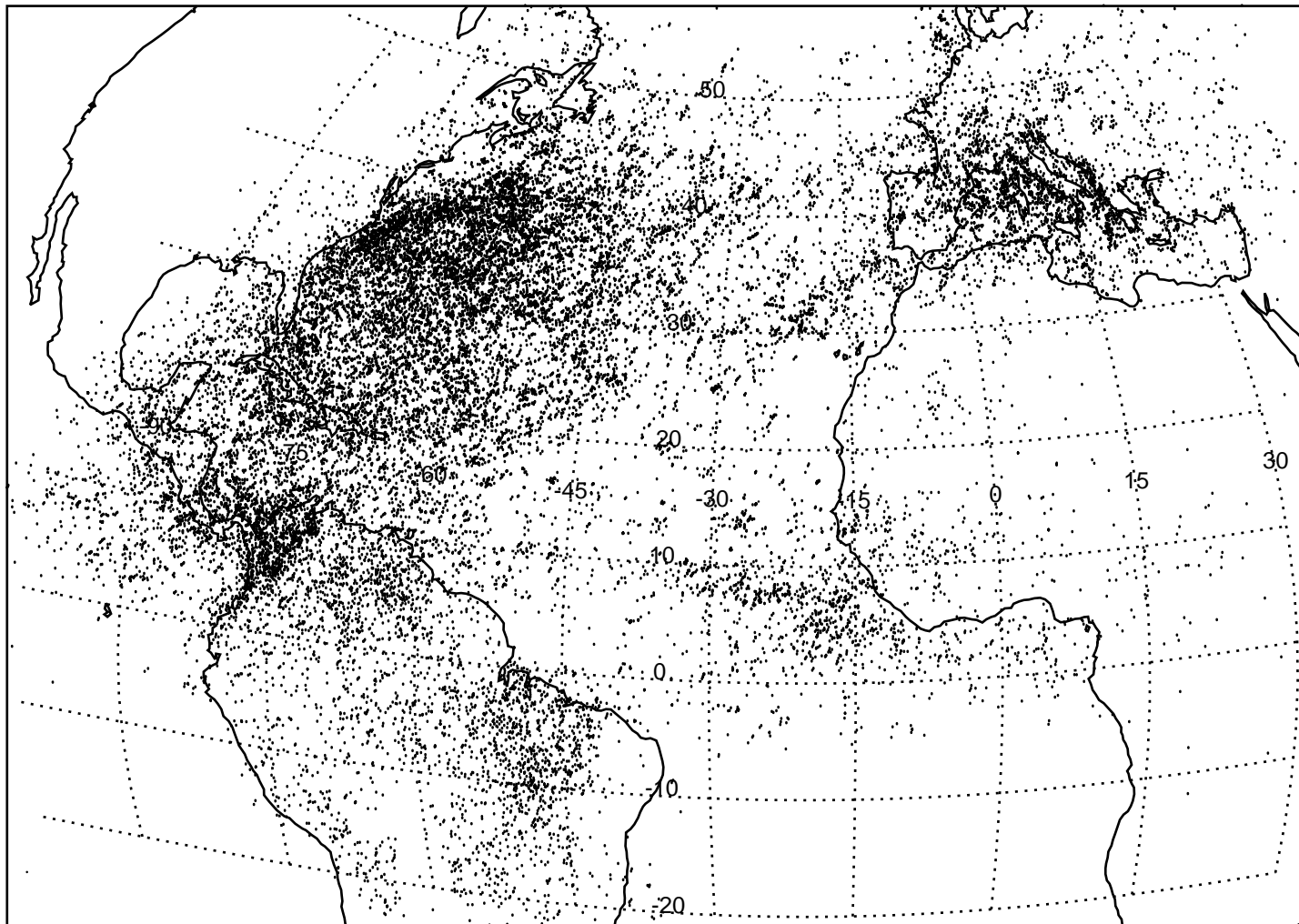


Figure B3: Map of all ATD-detected strokes occurring during intervals of FORTE visibility and being armed. Note the spectacularly sharp fall-off of event density going from sea to land on the United States southeast coast. Note also the departure of Gulf Stream from coastline north of Cape Hatteras.

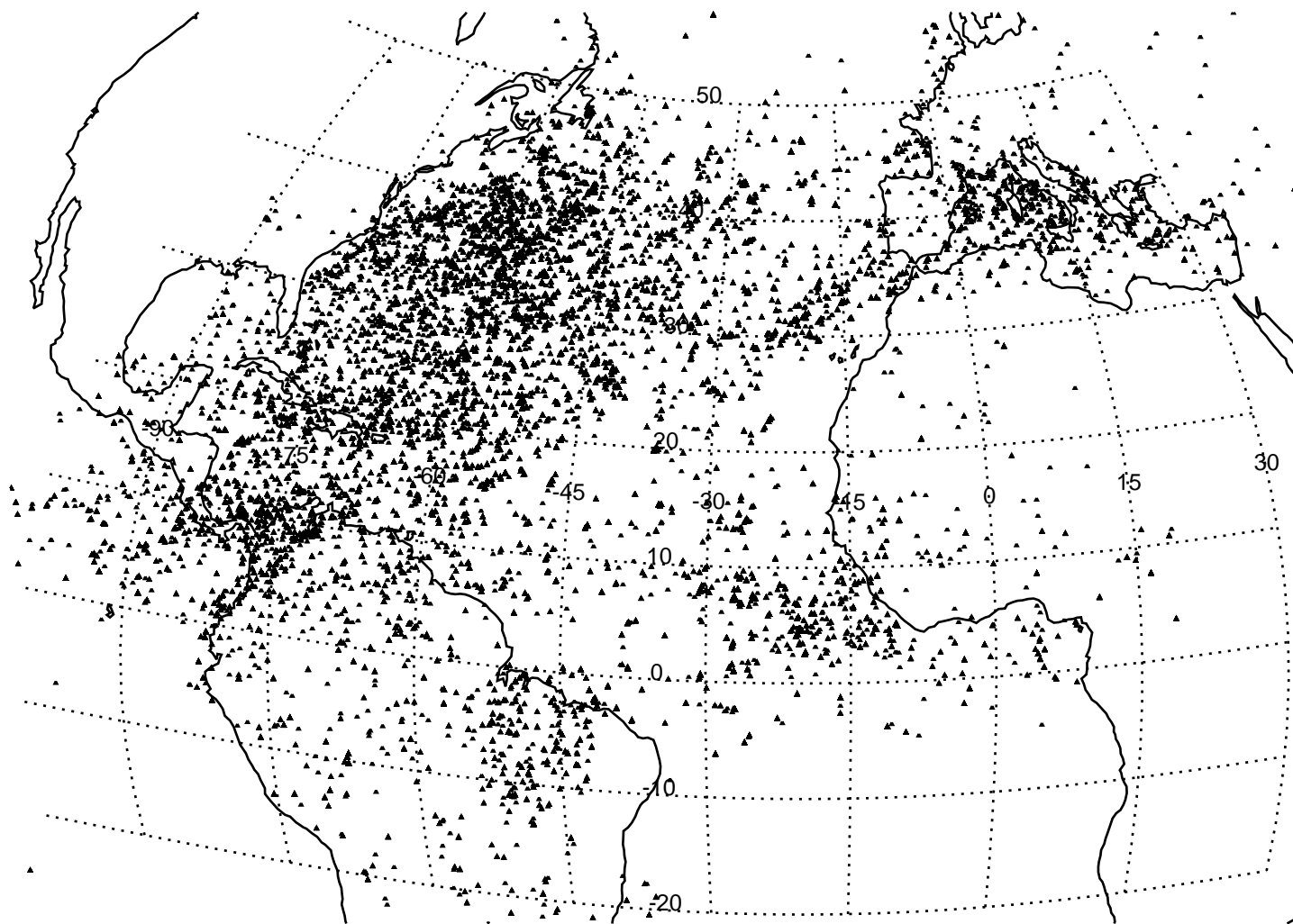


Figure B4: Map of ATD strokes which are accompanied by closely-coincident FORTE RF events. The mainly maritime location of these events mimics the location bias of the ATD parent distribution (see Figure B3).

Section C: pulse-pairs

Many FORTE RF signals consist of narrow ($<10\ \mu\text{s}$ fullwidth) pulses followed by a ground-reflection echo pulse. These have been called “transionospheric pulse pairs”, or TIPP. The emission height can be calculated from the measured inter-pulse time delay, if the horizontal (longitude, latitude) position of the lightning is known.

The map in Figure C1 shows the location of TIPP that are tightly coincident with ATD strokes, the location being inferred from the stroke location. We use these locations to infer the emission height (above the reflective ground) of the RF TIPP first pulse.

For NLDN/FORTE correlations, such an exercise had resulted in the emission-height distribution of Figure C2.

For the ATD/FORTE correlations, the emission-height distribution is shown in Figure C3. (Note the change of horizontal scale). Note the more bimodal height distribution in Figure C3, with the lower peak at 5-6 km, significantly lower than was the case with NLDN (see Figure C2). Also, the upper peak (at about 11 km) in Figure C3 is at lower altitude than the NLDN-coincident height max (12.5 km). We attribute this to differences in continental (a significant part of NLDN data, but not of the ATD data) versus maritime storm structure. Such a difference had already been seen when the NLDN/FORTE correlations were split into northern continental versus coastal/maritime in an earlier study (Jacobson, A.R., K.L. Cummins *et al*, FORTE radio-frequency observations of lightning strokes detected by the National Lightning Detection Network, *J. Geophys. Res.*, 105 (D12), 15,653, 2000.)

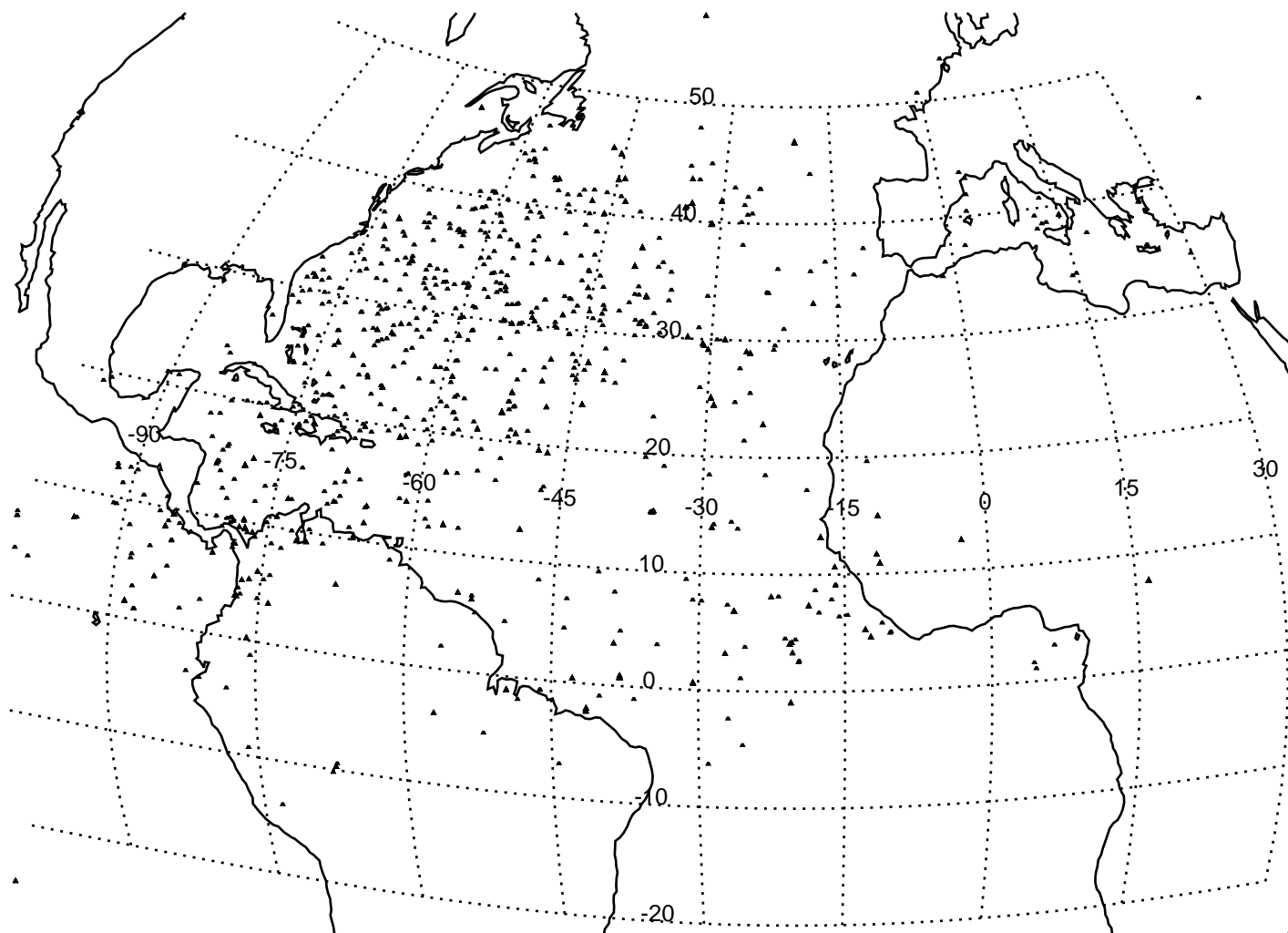


Figure C1: Map of ATD strokes which are coincident with FORTE RF pulse-pairs, in which the second pulse of a pair is due to a ground reflection.

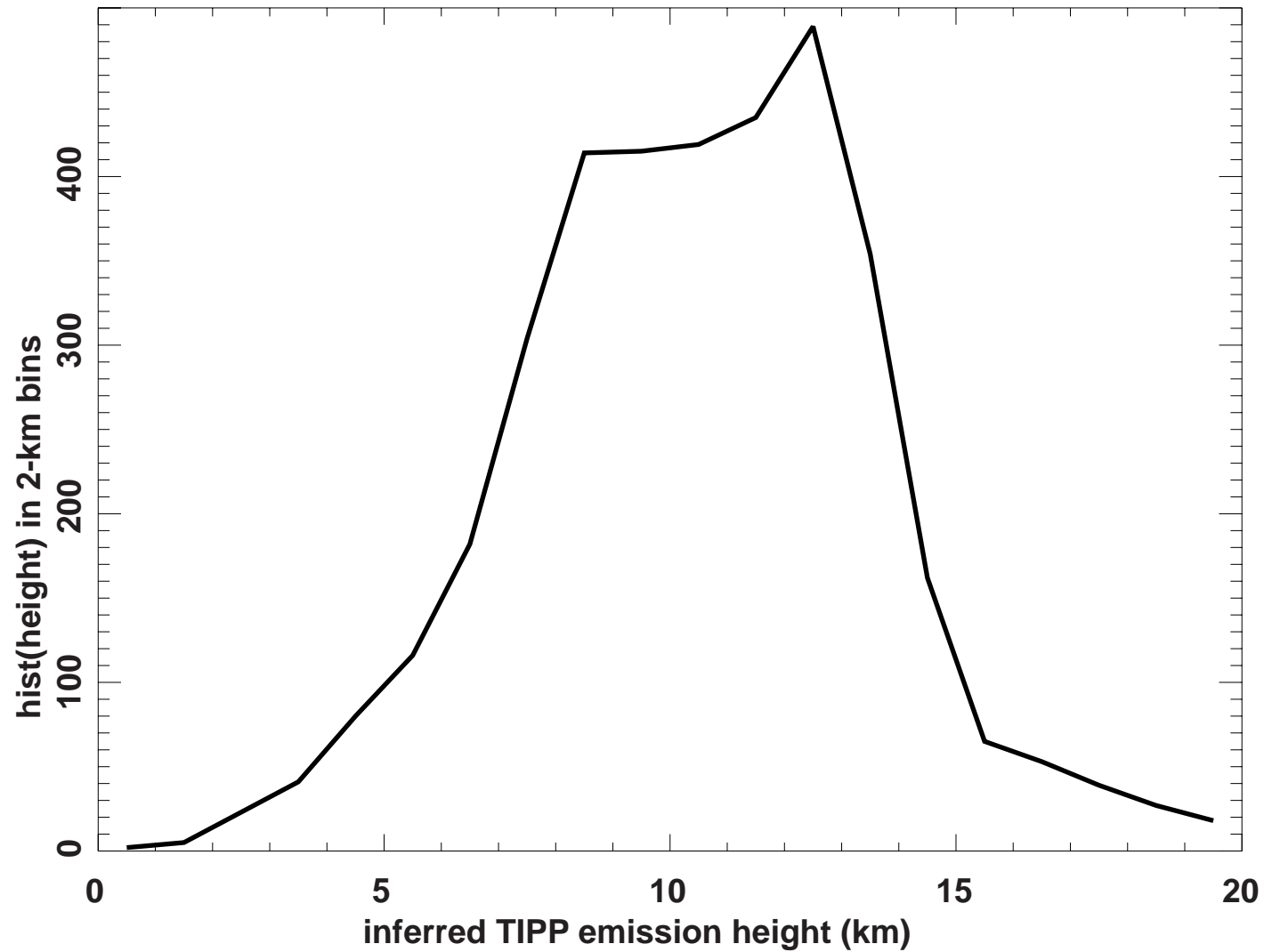


Figure C2: Distribution of emission heights (inferred from TIPP inter-pulse separation), in 2-km height bins, for FORTE pulses that are closely coincident with NLDN strokes and hence geolocated by NLDN. Note the broad height distribution from 7 to 15 km.

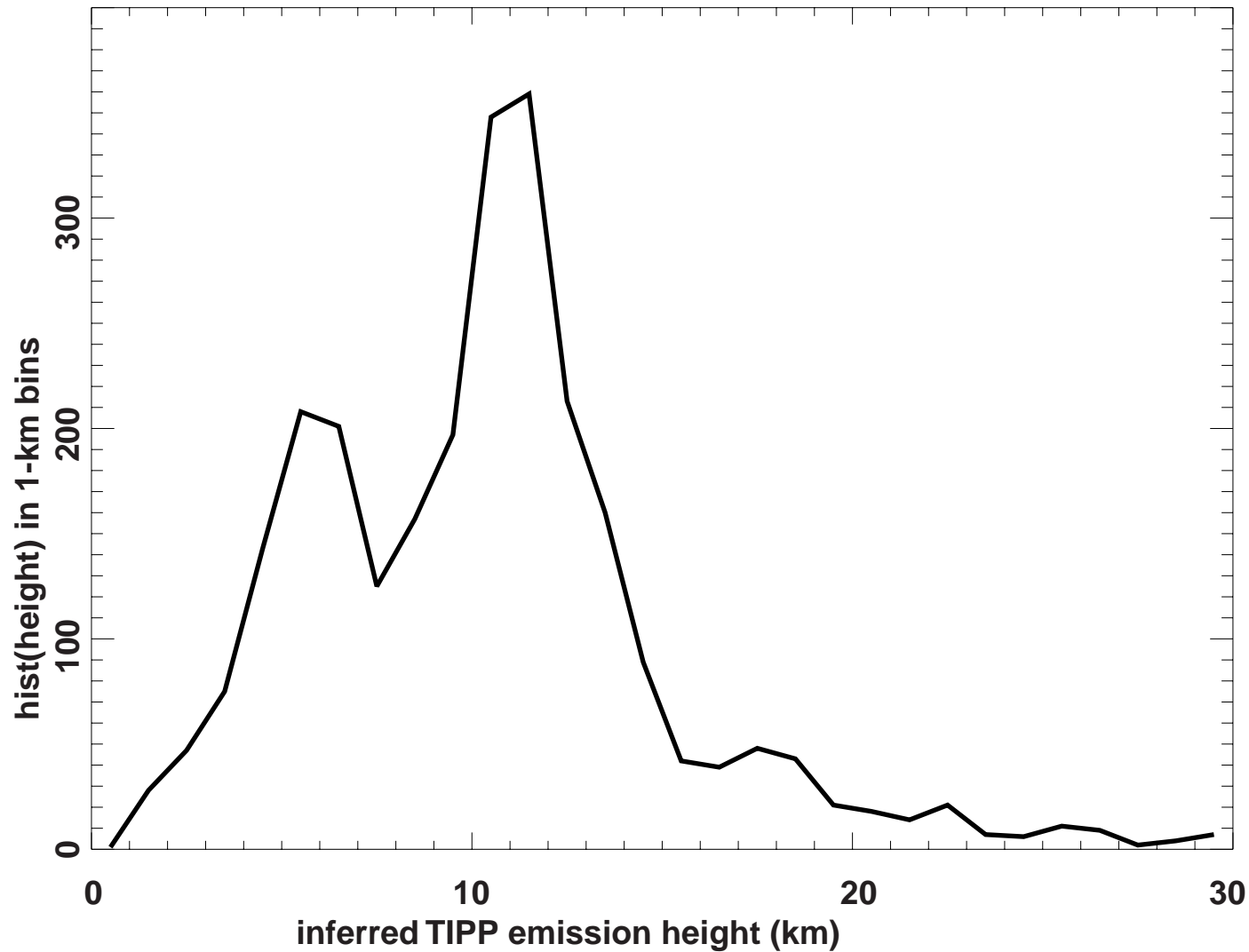


Figure C3: Distribution of emission heights (inferred from TIPP inter-pulse separation), in 1-km height bins, for FORTE pulses that are closely coincident with ATD strokes and hence geolocated by ATD. Note the more bimodal height distribution, with the lower peak at 5-6 km, significantly lower than was the case with NLDN (see Figure C2). Also, the upper peak (at about 11 km) is at lower altitude than the NLDN-coincident height max (12.5 km). We attribute this to differences in continental (part of NLDN data) versus maritime storm structure.